

1     **METHODS FOR ACQUIRING AND PROCESSING SEISMIC DATA FROM**  
2     **QUASI-SIMULTANEOUSLY ACTIVATED TRANSLATING ENERGY**  
3         **SOURCES**

4

5             TECHNICAL FIELD

6

7     The present invention relates generally to seismic exploration, and more  
8     particularly, to acquiring and processing seismic data generated from  
9     generally simultaneously activated seismic energy sources.

10

11             BACKGROUND OF THE INVENTION

12

13     In the hydrocarbon exploration industry, remote sensing of underground  
14     geological formations using seismic waves provides information on the location,  
15     shape, and rock and fluid properties of potential hydrocarbon reservoirs. The  
16     standard technique comprises the activation of a source of acoustic energy  
17     which radiates seismic waves into the earth. These seismic waves reflect from  
18     and refract through subsurface geologic layers (acoustic illumination or  
19     insonification). The recording of these seismic waves by many different  
20     receivers (pressure or motion sensors) are ideally situated so as to optimize the  
21     ratio of information obtained to cost. This basic  
22     sourcing/insonification/recording procedure is repeated many times at slightly  
23     different locations over a subsurface region of interest.

24

25     However, the resolution required of the seismic data for a detailed interpretation  
26     and adequate risk reduction can be suboptimal given the cost constraints  
27     inherent in seismic acquisition. Methods have been taught using generally  
28     simultaneously fired energy sources in an effort to obtain more information for a  
29     given cost.

30

31     Edington, U.S. Pat. No. 4,953,657 teaches a method of time delay source  
32     coding. In this method "a series of shots is made at each shotpoint with a  
33     determinable time delay between the activation of each source for each shot".

1 The “series of shots” refers to occupying each shotpoint location for several  
2 consecutive shots. This methodology may be acceptable for seismic  
3 acquisition on land where seismic sources can easily remain fixed at one shot  
4 location for an indefinite time. However, the method is not well suited for  
5 marine recording in which a seismic receiver cable is being towed behind a  
6 boat. A certain minimum velocity is necessary to preserve the approximately  
7 linear trajectory of the cable.

8

9 De Kok et.al, U.S. Pat. No. 6,545,944, teaches a method for acquiring and  
10 processing seismic data from several simultaneously activated sources. In  
11 particular, the method requires that several independently controllable “source  
12 elements” be activated in a fixed sequence, at successive neighboring  
13 locations. This activation sequence unavoidably smears the energy from a  
14 single effective source across several neighboring shot locations, necessitating  
15 an interpolation step and the introduction of unwanted interpolation noise.  
16 Further, the success of building an effective source by spatial sequencing of  
17 source sub-elements appears to depend sensitively on source timing precision  
18 and sea-state.

19

20 Beasley et al., U.S. Pat. No. 5,924,049 also teaches a method of acquiring and  
21 processing seismic data using several separate sources. In the preferred  
22 embodiment, it teaches that the sources can be activated sequentially with a  
23 constant inter-source time delay (up to 15 and 20 seconds). During the  
24 processing stage, the method requires anywhere from 2% to 33% of data  
25 overlap between panels of data from different sources. Further, it relies on  
26 conflicting dips to discriminate energy coming from different source directions,  
27 which requires a specific spatial relationship among the sources and the  
28 recording cable, and thus is not well suited to simultaneous signals arriving  
29 from approximately the same quadrant. In a subsidiary embodiment, the  
30 several sources can be activated exactly concurrently, in which case the  
31 sources are then arranged to emit signature-encoded wavefields. The  
32 decoding and signal separation associated with this type of concurrent  
33 signature encoding is usually unsatisfactory. Furthermore, the sources need to

- 1 be activated at both the leading and trailing ends of the spaced-apart receivers,
- 2 which is inflexible.

3

4 The present invention contrasts with the aforementioned inventions and  
5 addresses their shortcomings by teaching a novel way of acquiring and  
6 processing seismic data obtained from two or more quasi-simultaneously  
7 activated sources.

8

## SUMMARY OF THE INVENTION

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11 This invention teaches a method for the acquisition of marine or land seismic  
12 data using quasi-simultaneously activated translating seismic sources whose  
13 radiated seismic energy is superposed and recorded into a common set of  
14 receivers. Also taught is the subsequent data processing required to separate  
15 these data into several independent records associated with each individual  
16 source. Quasi-simultaneous acquisition and its associated processing as  
17 described herein enable high quality seismic data to be acquired for greater  
18 operational efficiency, as compared to a conventional seismic survey.

19

20 A method for obtaining seismic data is taught. A constellation of seismic  
21 energy sources is translated along a survey path. The seismic energy  
22 sources include a reference energy source and at least one satellite energy  
23 source. A number of configurations for the arrangement of the seismic  
24 sources and the locations of seismic receivers are disclosed. The reference  
25 energy source is activated and the at least one satellite energy source is  
26 activated at a time delay relative to the activation of the reference energy  
27 source. This activation of sources occurs once each at spaced apart  
28 activation locations along the survey path to generate a series of superposed  
29 wavefields which propagate through a subsurface and are reflected from and  
30 refracted through material heterogeneities in the subsurface. The time delay  
31 is varied between the spaced apart activation locations. Seismic data is  
32 recorded including seismic traces generated by the series of superposed  
33 wavefields utilizing spaced apart receivers.

1 The seismic data is then processed using the time delays to separate signals  
2 generated from the respective energy sources. More specifically, the  
3 processing of the seismic data further includes sorting into a common-  
4 geometry domain and replicating the seismic traces of data into multiple  
5 datasets associated with each particular energy source. Each trace is time  
6 adjusted in each replicated dataset in the common-geometry domain using  
7 the time delays associated with each particular source. This results in signals  
8 generated from that particular energy source being generally coherent while  
9 rendering signals from the other energy sources generally incoherent. The  
10 coherent and incoherent signals are then filtered to attenuate incoherent  
11 signals using a variety of filtering techniques.

12

13 It is an object of the present invention to provide a method for acquisition of  
14 seismic signals generated “quasi-simultaneously” from several moving  
15 separated sources activated with a small time delay, and their subsequent  
16 accurate separation during data processing into independent data sets  
17 exclusively associated with each individual source. This can greatly improve  
18 operational efficiency without compromising data resolution.

19

20 BRIEF DESCRIPTION OF THE DRAWINGS

21

22 The following drawings illustrate the characteristic acquisition and processing  
23 features of the invention, and are not intended as limitations of these  
24 methods.

25

26 FIG. 1 is a plan view of the acquisition of seismic data using the invention with  
27 two quasi-simultaneous sources;

28

29 FIG. 2 is a profile view of the acquisition of seismic data corresponding to FIG.  
30 1;

31

32 FIG. 3 illustrates the activation time delays being composed of a constant part  
33 and a variable part;

1 FIG. 4 is a common-shot gather showing the coherent superposed signals  
2 from the reference and satellite sources;

3

4 FIG. 5 is a common-midpoint gather showing the coherent signals from the  
5 reference source and the incoherent noise from the satellite source;

6

7 FIG. 6 compares migrated results from both conventional (one-source)  
8 acquisition and multiple quasi-simultaneously activated sources; and

9

10 FIG. 7 is a flowchart summarizing the acquisition, trace-sorting, and noise  
11 attenuation segments of this invention.

12

13 **DETAILED DESCRIPTION OF THE PREFERRED EMODIMENTS FOR THE**  
14 **INVENTION**

15

16 This invention teaches a method for the acquisition of seismic data using quasi-  
17 simultaneous sources, as well as the processing of the superposed signals in  
18 order to separate the energy due to each source from the energy due to every  
19 other source in the constellation. For the purposes of this invention, the term  
20 “constellation” shall mean the set of spaced apart seismic sources bearing any  
21 relative spatial relationship among themselves, and able to move as a whole  
22 from one location to another as part of a seismic survey.

23

24 Quasi-simultaneous acquisition and its associated processing as described  
25 herein enable high quality seismic data to be acquired at a much greater  
26 operational efficiency as compared to a conventional seismic survey. The term  
27 “quasi-simultaneous” shall mean that the activation-time differences among the  
28 several sources in a constellation are not zero (thus the prefix “quasi”), but yet  
29 small enough (typically less than several seconds) so as not to interfere with  
30 the previous or succeeding shots of the seismic survey, viz., less than the  
31 recording (or “listening”) time of a shot record (thus the term “simultaneous”:  
32 operationally simultaneous). Acquisition, trace sorting and time correction, and  
33 noise attenuation filtering are described in turn.

1   **ACQUISITION**

2  
3   The first step is to acquire seismic data generated by quasi-simultaneous  
4   sources. Referring to FIG. 1, in the most preferred embodiment, the  
5   acquisition involves three-dimensional marine seismic surveying employing a  
6   seismic vessel **10** towing a reference source **11** and several trailing streamers  
7   **12** which contain seismic receivers, along with at least one other spaced apart  
8   satellite source **14**, which is itself towed by a spaced apart vessel **13**. The term  
9   “reference source” shall mean the source which is fired at seismic recording  
10   time zero. It can be the source nearest the recording cable (if source and cable  
11   are being towed by the same vessel in marine recording), or for example it can  
12   be the source in the constellation which is activated first. In all cases, the  
13   satellite source time delays are with respect to the reference source. For  
14   identification purposes, the constellation’s location can be identified with that of  
15   the reference source. The term “satellite source” shall refer to any one of the  
16   energy sources other than the reference source. The term “time delay”,  
17   abbreviated “ $T_d$ ” shall mean a positive or negative time interval with respect to  
18   the reference source and recording time 0, and which is the sum of a positive or  
19   negative constant part (here abbreviated by “ $T_c$ ”) and a positive or negative  
20   variable part (here abbreviated by “ $T_v$ ”).

21   Thus  $T_d = T_c + T_v$ . For the reference source,  $T_d = 0$ .

22  
23   Alternatively, vessel **13** and source **14** could be located (not shown) collinearly  
24   with and downstream from the streamer. These configurations in which the  
25   reference and satellite sources are collinear with the set of receivers provide  
26   extra offsets as compared to a conventional single-source operation.  
27   Preferably, the separation distance between the leading edge of the streamers  
28   **12** and the upstream source **14** may be about the length of the streamers **12**.  
29   Likewise the separation distance between the trailing edge of the streamers **12**  
30   and the downstream source **14** (not shown) may be about the length of the  
31   streamers **12**.

1 Those skilled in the art will appreciate that the acquisition may also be  
2 accomplished, by way of example and not limitation, with a source **19** towed  
3 by a vessel **18** near the tail end of the receiver cable and between two of the  
4 several streamers **12**, or with a source **16** towed by a vessel **15**  
5 perpendicularly displaced from the direction of the receiver cable, with a  
6 source towed by a boat trailing the tail end of the receiver cable by a fixed  
7 amount, or even with a second independent source **17** towed behind vessel  
8 **10**. The configuration in which the satellite source is perpendicularly displaced  
9 from the streamer of receivers provides extra azimuths as compared to a  
10 single-source operation. Further, those skilled in the art will appreciate that  
11 cables of receivers can be towed behind more than one vessel, or that the  
12 seismic receivers need not be towed behind a marine vessel but can be fixed  
13 to the earth as in land recording, ocean-bottom recording, and marine vertical-  
14 cable recording, among others.

15

16 FIG. **2** is a profile view of the collinear acquisition geometry of FIG. **1**. The  
17 reference source **11** (with indicated earth coordinates  $S_1$ ) is situated on the  
18 recording surface **20** (generally the surface of the Earth) and generates  
19 seismic energy **22** which travels down to a geologic reflector **21** and is  
20 reflected back toward the receiver cable **12** (one of whose receivers has the  
21 indicated earth coordinates  $R$ ). Meanwhile, the satellite source **14** (with  
22 indicated earth coordinates  $S_2$ ) is activated quasi-simultaneously and it also  
23 generates seismic energy **23** which reflects back into the receiver cable,  
24 where it superposes with the signal from the reference source **11** and where  
25 both are recorded.

26

27 FIG. **4** shows a common-shot gather illustrating the superposition of energy  
28 from two quasi-simultaneous sources. A receiver cable **43** records seismic  
29 energy along a recording time axis **42**. The reference source energy **40** and  
30 satellite source energy **41** are interfering and superposed on each trace of the  
31 common-shot gather.

1 Given a current location of the constellation within the seismic survey, its Ns  
2 sources are activated quasi-simultaneously. The term “Ns” shall refer to the  
3 number of spaced apart sources populating the constellation. FIG. 3 illustrates  
4 the quasi-simultaneous timing scheme for the case of Ns=4. The constellation  
5 of sources is quasi-simultaneously activated at times 30 determined by the  
6 interval of time required for the constellation to translate between successive  
7 shot locations, which is generally the translation distance divided by the  
8 constellation velocity. Most preferably, a Global Positioning System is used to  
9 activate the reference activation source at predetermined intervals, for example  
10 25 meters. The quasi-simultaneous source activation-time delay  $T_d$  33 (with  
11 respect to the reference source) is different for each source within the  
12 constellation, and is a sum of two parts. The first component is a  
13 predetermined positive or negative constant  $T_c$  31 for a given source in the  
14 constellation but can be different for different sources. Its optimum value is  
15 dictated by the operational need to capture all of the desired signal from that  
16 source into the seismic receivers during the current recording time window, and  
17 so depends on the specific acquisition geometry. It can be different for each  
18 source in the constellation, but is constant over the course (duration) of the  
19 survey (as long as the constellation geometry does not change). In the case of  
20 a satellite source collinear with the seismic streamer as in FIG. 1, this time  
21 might be, for example, several seconds in advance of (negative number) the  
22 near-streamer reference source activation time.

23  
24 The second component is a predetermined variable time delay  $T_v$  32 which is  
25 different for each source in the constellation, and also changes with each  
26 succeeding location of the constellation within the seismic survey. In the  
27 preferred embodiment this variable component is a predetermined positive or  
28 negative random value whose value ranges from plus to minus ten times the  
29 source waveform’s dominant period, although greater times are also possible.  
30 This random time dithering introduces a source-specific time-delay encoding  
31 (not signature encoding) among the several sources within the constellation,  
32 whose resultant wavefields are all superposed in the recording cable. Although  
33 not necessary, it may be beneficial to prevent successive random values of  $T_d$

1 to be too close to one another. This can be avoided by requiring that  
2 successive values of  $T_d$  be differentiated by a predetermined minimum positive  
3 or negative value. This can be accomplished simply by generating a  
4 replacement random value that is satisfactory. This overcomes the potential  
5 problem of "runs" of the same value in a random sequence, which when applied  
6 to the source time delays might create short patches of coherence where none  
7 is desired.

8

9 Although  $T_c$  and  $T_v$  are both predetermined, it is only their sum  $T_d$  that is  
10 required in processing, and due to possible slight variation in actual source  
11 activation times,  $T_d$  must be accurately measured and recorded during  
12 acquisition.

13

14 The entire seismic survey then consists of quasi-simultaneously activating the  
15 entire constellation once at each geographic location in the survey (at resultant  
16 times 30), and then moving the constellation a predetermined amount to a new  
17 location, and repeating the quasi-simultaneous source activation procedure.

18

## 19 **COMMON-GEOMETRY TRACE SORTING AND TRACE TIME- 20 CORRECTION**

21

22 Trace sorting will now be described. After acquisition, each trace contains  
23 superposed seismic signals (reflections, refractions, etc.) from each of the  $N_s$   
24 sources. The first stage in separating the signals from the constellation's  
25 several sources is to spatially reorganize the seismic traces from the common  
26 shot gathers into a suitable domain in which the signal from each successive  
27 source in the constellation can be selectively made coherent and all others  
28 made incoherent. As illustrated in FIG. 2, each trace includes a trace header  
29 which contains, among other information, earth coordinates of the receiver  
30 and the  $N_s$  sources, as well as the time delays  $T_d$  for each of the  $N_s - 1$  satellite  
31 sources. The common-shot gathers are resorted  $N_s$  times, once for each  
32 source in the constellation. Each resorting follows the conventional procedure  
33 in which each given trace is placed into a particular common-geometry gather

1 of traces, depending on the source and receiver coordinates and the type of  
2 common-geometry desired. For example, common midpoint sorting dictates  
3 that the algebraic average of the source and receiver coordinates be a  
4 constant. Constant offset sorting dictates that the distance from source to  
5 receiver be a constant. Because the trace header contains the coordinates  
6 from Ns sources (two in the case of FIG. 2), the current trace is replicated and  
7 associated with Ns different midpoints or Ns different offsets, etc., one  
8 associated with each of the Ns sources.

9

10 For each of the Ns sources with which the trace is in turn identified, the time  
11 delay associated with that trace and source (and which is recorded in header  
12 **24**) is applied in reverse to the trace timing. Thus, subtracting the time delay  
13 Td from the trace time allows the signals in the seismic trace from that source  
14 to align with similar signals on other traces within the particular constant-  
15 geometry gather, and coherent signals from that source are formed.

16

17 In the preferred embodiment the traces are resorted into Ns common-midpoint  
18 domains, each common-midpoint domain associated with a particular source of  
19 the constellation. As a visual aid, FIG. 5 shows a common-midpoint gather  
20 from the same dataset as FIG. 4, and contains data ordered along an offset  
21 axis **53** and a time axis **52**.

22

23 Those skilled in the art will appreciate that other resorting may also be  
24 realized, by way of example and not limitation, by resorting the traces into  
25 common-offset domains (useful for some kinds of prestack depth migration),  
26 common-receiver domains (useful for recording and migration involving  
27 acquisition via vertical marine cable, vertical seismic profile in a well, or  
28 ocean-bottom cable), common-azimuth domains (useful for illumination within  
29 subsurface shadow zones), or indeed any other common-geometry domain in  
30 which subsequent data processing will occur. In each case, resorting the  
31 traces independently associates each common-geometry domain with a  
32 particular one of the Ns sources in the constellation.

1 In this resorted and time-corrected domain, each source's signal in turn  
2 becomes coherent and the signal from all other Ns-1 sources is made  
3 incoherent and appears as random noise. In this way the signal from each one  
4 of the Ns sources is made to "crystallize" into coherence at the expense of the  
5 other Ns-1 sources, producing Ns different datasets, one for each source of the  
6 constellation. This is illustrated in FIG. 5, in which the seismic signal **50** from  
7 the reference source has been made coherent, while the seismic signal from  
8 the satellite source has been turned into incoherent random noise which is  
9 scattered throughout the common-midpoint gather.

10

## 11 NOISE-ATTENUATION FILTERING

12

13 The next step is filtering out the unwanted noise from each of the resorted  
14 datasets. There are several approaches, depending on the particular common-  
15 geometry domain and whether the data are migrated or not. In the preferred  
16 embodiment, random noise suppression is applied to common-midpoint  
17 gathers in which coherent signal events tend to assume a hyperbolic trajectory  
18 while random noise does not follow any particular trajectory. The coherent  
19 signal events are localized in Radon space whereas the random noise is not  
20 localized in Radon space. Muting out unwanted noise events in Radon space  
21 followed by an inverse mapping to conventional time-offset space attenuates  
22 the random noise. The remaining signal can be used directly, but also can  
23 itself be time shifted back into decoherence, at which point it can be subtracted  
24 from the complementary gathers associated with the other sources prior to their  
25 Radon filtering.

26

27 Those skilled in the art will appreciate that random noise attenuation may also  
28 be accomplished, by way of example and not limitation, by other techniques  
29 such as stacking, F-X filtering, and also by Dynamic Noise Attenuation: This  
30 method is taught in a patent application entitled "Method for Signal-to-Noise  
31 Ratio Enhancement of Seismic Data Using Frequency Dependent True  
32 Relative Amplitude Noise Attenuation" to Herkenhoff et.al., USSN 10/442,392.  
33 The DNA Method is an inverse noise weighting algorithm, which can often be a

1 powerful noise attenuation technique and can be used in conjunction with other  
2 techniques in any common-geometry domain. The disclosure of this patent  
3 application is hereby incorporated by reference in its entirety. The particular  
4 importance of this specific step lies in its ability to largely preserve the relative  
5 amplitudes of the coherent signals in a gather in the presence of random noise,  
6 thus minimizing the effect of amplitude bias.

7

8 Because attenuation of random noise often amounts to a localized summing  
9 over signal trajectories to achieve so-called “root-n” noise reduction, different  
10 signal domains require different summing trajectories. Further, because even  
11 an approximate velocity model is useful to define signal trajectories as part of  
12 the migration summation process, random noise attenuation may be  
13 accomplished by taking advantage of the signal/noise separation powers  
14 inherent in seismic imaging. Given a velocity model, migration sums events  
15 over a very large aperture (an areal aperture in the case of three-dimensional  
16 migration), greatly attenuating random noise. In FIG. 6, the results of migrating  
17 with a known earth velocity are shown for both a conventional single-source  
18 acquisition (left panel) and the two-source quasi-simultaneous acquisition  
19 (some gathers from which are shown in FIGS. 4 and 5). Evidently for this  
20 dataset migration summing has effectively attenuated the random noise  
21 permeating the two-source input gathers from FIG. 5. More importantly, when  
22 applied in the common-offset domain, migration produces noise-attenuated  
23 common-offset volumes that preserve the prestack AVO information. It is this  
24 property that makes the common-offset embodiment particularly attractive.  
25 Note that velocity analysis (needed for the migration), which measures  
26 semblance, will work even on CMP gathers in which the random noise has not  
27 been attenuated. Alternatively, migration of quasi-simultaneous source data  
28 even with a suboptimal velocity function, followed by filtering, followed by  
29 demigration using the same velocity function can also attenuate random noise.  
30 All of the above techniques are equally preferred. Finally, one skilled in the art  
31 can appreciate that noise attenuation can also be realized by a concatenation  
32 of multiple processing steps such as those described above.

1 The foregoing segments detailed by this invention are summarized in flowchart  
2 form in FIG. 7. At each successive location of the constellation within the  
3 seismic survey, a master source timer 70 communicates the appropriate time  
4 delay 71 ( $T_d$ ) to each of the  $N_s - 1$  satellite sources 72. (The reference source,  
5 by definition above, has a total time delay of zero.) The sources are thus  
6 activated quasi-simultaneously, their energy enters and interacts with the earth  
7 layers 73, and the reflected and scattered waves are recorded by a common  
8 set of spaced apart receivers 74. The time delays  $T_d$  associated with each  
9 source are also recorded in 74.

10

11 After acquisition, each trace contains seismic events (reflections, refractions,  
12 etc.) from each of the  $N_s$  sources. The seismic data are resorted into  $N_s$   
13 common-geometry datasets 75 as explained in the reference to FIG. 2 above  
14 (such as common-midpoint or common-offset, two particularly good and  
15 preferred domains). Then the traces in each of the  $N_s - 1$  satellite source  
16 datasets have applied to them the negative time delay 76 associated with that  
17 trace and that satellite source. Lastly,  $N_s$  noise-attenuation filtering operations  
18 77 can be applied, because in each of the  $N_s$  data volumes the energy from  
19 only one source appears coherent, while the energy from all other sources  
20 appears as incoherent noise.

21

22 While in the foregoing specification this invention has been described in  
23 relation to certain preferred embodiments thereof, and many details have  
24 been set forth for purpose of illustration, it will be apparent to those skilled in  
25 the art that the invention is susceptible to alteration and that certain other  
26 details described herein can vary considerably without departing from the  
27 basic principles of the invention.